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Spin-isospin responses of ^{71}Ga for solar neutrinos studied by $^{71}\text{Ga}({}^3\text{He}, t\gamma){}^{71}\text{Ge}$ reaction

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Abstract

The charge-exchange $^{71}\text{Ga}({}^3\text{He}, t\gamma){}^{71}\text{Ge}$ reaction was used to study the spin-isospin (Gamow Teller: GT) excitations relevant to the axial-vector charged-weak response for solar neutrinos. High-lying GT states in ^{71}Ge with excitation energies up to one MeV above the neutron threshold were found to have finite γ -decay branches to low-lying states. The GT strengths for relevant states and absorption rates of solar neutrinos through the $^{71}\text{Ga}(\nu, e){}^{71}\text{Ge}$ and $^{71}\text{Ga}(\nu, e\gamma){}^{71}\text{Ge}$ reactions were derived. © 1998 Elsevier Science B.V. All rights reserved.

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Interest in the nuclear spin-isospin responses [1–4] has recently increased in view of both particle and nuclear physics aspects. The particle physics aspect is concerned with axial-vector charged-weak processes associated with neutrino (ν) nuclear interactions. One of the key issues is the possible ν -oscillation due to finite ν -mass differences and finite ν -flavor mixings. They are studied by detecting the

solar- ν through inverse beta decays and ν -electron scatterings [5–9]. Nuclear spin-isospin responses relevant to axial-vector charged-weak processes of ν are crucial for getting the solar- ν flux by inverse β decays. The nuclear physics aspect is concerned with spin-isospin strength distributions and their particle and γ -decays, which are relevant to spreading and escape widths of spin-isospin resonances. Major

components of nuclear spin-isospin responses in case of low-momentum-transfer processes are the Gamow-Teller (GT) ones with angular momentum and parity transfer of $\Delta J^\pi = 1^+$.

^{71}Ga has exclusively been used for detecting the major component of solar neutrinos, the low-energy pp neutrinos, through the inverse beta (β) decays of $^{71}\text{Ga}(\nu, e)^{71}\text{Ge}$ and $^{71}\text{Ga}(\nu, e \gamma)^{71}\text{Ge}$ processes because of the very low Q_β value of 0.236 MeV. Level and decay schemes associated with the ^{71}Ga solar- ν detectors are shown in Fig. 1. The GT states with spins and parities of $J^\pi = 5/2^-, 3/2^-$ and $1/2^-$ in ^{71}Ge are populated by GT (1^+) excitations from ^{71}Ga with $J^\pi = 3/2^-$. The neutron and proton separation energies of ^{71}Ge to the 0^+ and 1^+ ground states of ^{70}Ge and ^{70}Ga are, respectively, $S_n = 7.41$ MeV and $S_p = 8.29$ MeV. The states in the transition region from $E_x = 7.41$ MeV to around $E_x \sim 9$ MeV may have finite γ -branches, and thus contribute to the production of ^{71}Ge , depending on the spin, parity, isospin and other properties of the states.

The present work aims at measuring quantitatively the solar- ν absorption rate including the contributions of these unbound states to the population of the ground state of ^{71}Ge through γ -decays to bound states in ^{71}Ge .

Recently, it has been shown at RCNP, Osaka [10] that spin-isospin (GT) strengths can be well investigated by the charge exchange ($^3\text{He}, t$) reaction at a bombarding energy of 150 MeV/A, where spin-isospin modes are preferentially excited. GT strengths

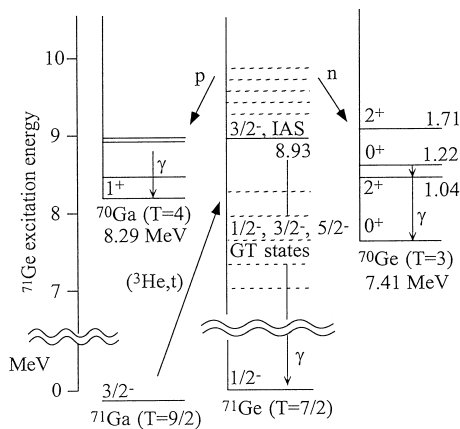


Fig. 1. Level and decay schemes of GT states with $1/2^-$, $3/2^-$ and $5/2^-$ in ^{71}Ge . Energies are given in units of MeV.

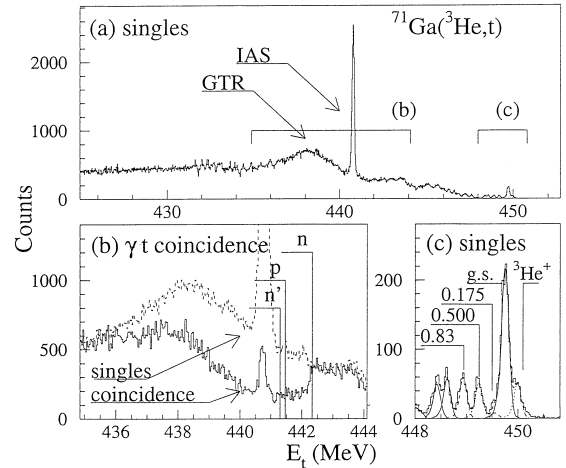


Fig. 2. Energy spectrum of tritons from the $^{71}\text{Ga}(^3\text{He}, t)^{71}\text{Ge}$ reaction. IAS and GTR stand for the isobaric analogue state and the GT giant resonance, respectively. Arrows with n, p and n' are the neutron and proton threshold (binding) energies, and that for neutrons feeding the 2^+ excited state in ^{70}Ge , respectively. (a) Top: The singles triton spectrum. (b) Bottom: The singles and coincidence triton spectra. (c) Expanded singles spectrum for low-lying states in ^{71}Ge [10]. Energies are given in units of MeV.

for individual states and particle and γ -decay branches from GT states have been studied [11]. Therefore we used the $^{71}\text{Ga}(^3\text{He}, t)^{71}\text{Ge}$ reaction to excite the GT states in ^{71}Ge . The 450 MeV ^3He beam from the RCNP ring cyclotron was used to bombard a metallic, 2 mg/cm² thick ^{71}Ga target. The triton ejectiles were detected at forward angles of $\theta_t = 0^\circ - 2^\circ$ in order to select preferentially the GT excitations. They were momentum-analyzed by means of the high-resolution spectrometer GRAND RAIDEN. Six NaI detectors ($3'' \phi \times 6''$) were used to detect decaying γ -rays in coincidence with the tritons. The γ -rays were detected at $\theta_\gamma = 125^\circ$ with respect to the ^3He (and t) beam axis, where the effect of the angular distribution vanishes because of $P_2(\cos \theta_\gamma) \approx 0$. The overall energy resolution for the tritons was around $\Delta E_t \sim 300$ –400 keV, and that for the γ -rays was around $\Delta E_\gamma \sim 100$ –300 keV for $E_\gamma = 1.5$ –5 MeV. The experimental set-up was the same as used in Ref. [12].

The observed singles and coincidence triton spectra are shown in Fig. 2. The singles spectrum shows a sharp peak of IAS at $E_x = 8.93$ MeV and a broad bump of the GT resonance at around $E_x = 12$ MeV.

The low-lying GT states are clearly seen. The GT strength for the 175 keV first excited state is only 5% of that for the ground state. The t - γ coincidence rate drops immediately after the excitation energy E_x gets beyond the neutron threshold energy S_n . This is because of the opening of the neutron channel to the 0^+ ground state in ^{70}Ge (see Fig. 2b). It is interesting to note that the coincidence rate is still relatively large even above S_n . It remains as large as almost 50% of the value below S_n until E_x exceeds the threshold energy $S_{n'}$ for neutron decay to the 2^+ excited state in ^{70}Ge . The γ -coincidence rate increases as the excitation energy increases further above $S_{n'}$, as shown in Fig. 2b. This is mainly because of the increased neutron decay branch to the first-excited state in ^{70}Ge and neutron and proton decay branches to excited states. Note that these excited states decay by emitting low-energy γ -rays to ^{70}Ge and ^{70}Ga , resulting in the increased γ -coincidence rate. The large γ -coincidence rates at the higher excitation region are due to the large γ -ray multiplicity. Actually, direct γ -branches to low-lying states in ^{71}Ge decrease rapidly as E exceeds $S_{n'}$. This is seen in the absence of direct high-energy γ -rays in the γ -ray spectrum in the region of $E_x > S_{n'}$ (see Fig. 3c), as discussed later.

The shape of the γ -ray coincidence spectrum does not change drastically below and above the neutron threshold S_n , suggesting similar γ -cascade processes to low-lying states in ^{71}Ge , as shown in Fig. 3a and b. On the other hand, high-energy γ -rays vanish and low-energy ones, including the 1.04 MeV $2^+ \rightarrow 0^+$ γ -ray in ^{70}Ge , become conspicuous in the region above $S_{n'}$, indicating major neutron and proton decay channels followed by low-energy γ -rays.

These observed features suggest that a half of the excited states in the excitation energy interval between S_n to $S_{n'}$ decays by emitting neutrons to the ground state in ^{70}Ge , and the other half by emitting γ -rays to low-lying states in ^{71}Ge . Excited states just above $S_{n'}$ decay by emitting neutrons to the 2^+ and other excited states in ^{70}Ge , which are followed by de-exciting γ -rays. Higher excited states decay by emitting either neutrons to ^{70}Ge or protons to ^{70}Ga .

The γ -ray branching ratio Γ_γ/Γ_T is deduced from the single and two-hit coincidence rates as $\Gamma_\gamma/\Gamma_T = (Y_c/Y_s)/\varepsilon_\gamma$, where the coincidence rate Y_c/Y_s is the ratio of the γ -coincidence triton yield Y_c to the

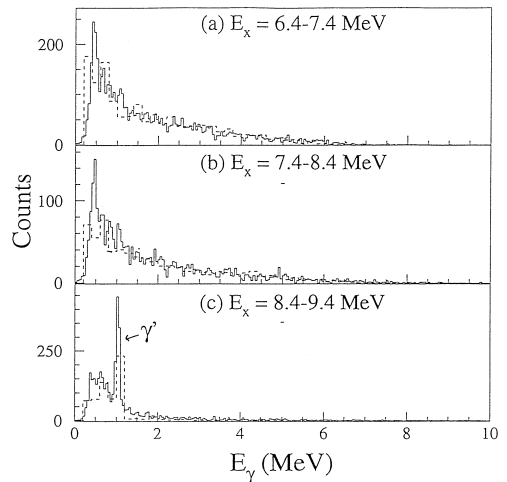


Fig. 3. Coincidence γ -ray spectra from the $^{71}\text{Ga}(^3\text{He}, \gamma)$ reaction. (a), (b) and (c) stand for the γ -ray spectra for the particle-bound region, $E_x = 6.4$ – 7.4 MeV, for the neutron quasi-bound region, $E_x = 7.4$ – 8.4 MeV, and for the particle-unbound region, $E_x = 8.4$ – 9.4 MeV. Here, $E_x = 7.4$ and 8.4 MeV correspond to the neutron separation energies S_n and $S_{n'}$ to the ground and first-excited states, respectively. In (c), γ' corresponds to the γ -ray from the first-excited state in ^{70}Ge (see Fig. 1). Dotted lines are simulations by GEANT code making use of CASCADE-code calculations.

singles one for one NaI detector, and ε_γ is the over-all γ -ray efficiency. The γ -coincidence yield is given approximately by the sum, $Y_c(1)$ and $Y_c(2)/2$, where $Y_c(1)$ is the yield of the single-hit events with γ -signals only from one of the NaI detectors and $Y_c(2)$ is that of the two-hit events with two γ -signals, one from the same NaI detector and one from any other detector. Since the γ -ray hitting the NaI detector in the two-hit events can be either the first or the second one, $Y_c(2)$ is divided by a factor 2 to avoid double counting. The higher multi-hit contributions are negligibly small.

The over-all efficiency ε_γ for detecting γ -rays of the present interest depends on the detector characteristics such as size, distance from target, the energy discrimination level and on the γ -ray spectrum, i.e. the energy and multiplicity of the emitted γ -rays. Thus, it changes as the excitation energy E_x changes. The efficiency ε_γ was estimated as a function of E_x as N_d/N_0 , where N_0 is the number of γ -rays emitted from the GT states at E_x and N_d is the number of γ -rays detected by one NaI detector.

The CASCADE code [13] was used to evaluate the γ -ray spectrum emitted isotropically over the full solid angle, while the GEANT code [14] was used to simulate the γ -ray spectrum to be detected in one of the NaI detectors. Actually, all the coincidence signals from the six detectors were used to get better statistics since they were set at the same angles of $\theta_\gamma = 125^\circ$ with respect to the ^3He beam (note the t is detected at 0° along the ^3He beam). The CASCADE-code and GEANT-code calculations were checked by comparing relative shapes of the calculated and observed spectra, as shown in Fig. 3. Obtained branching ratios are shown as function of excitation energy in Fig. 4.

The γ -ray branching ratio Γ_γ/Γ_T in the particle-bound region of $E_x < S_n$ is 100%, but is about 50% in the region from $E_x = S_n$ to $E_x = S_{n'}$. It decreases rapidly as E_x goes beyond $S_{n'}$ because of neutron and proton decays to excited states in ^{70}Ge and ^{70}Ga , respectively. Therefore direct γ branches to low-lying states in ^{71}Ge become negligible above $S_{n'}$. This explains the observation in Fig. 3c that high energy γ -rays above 2 MeV almost vanish just above $S_{n'}$.

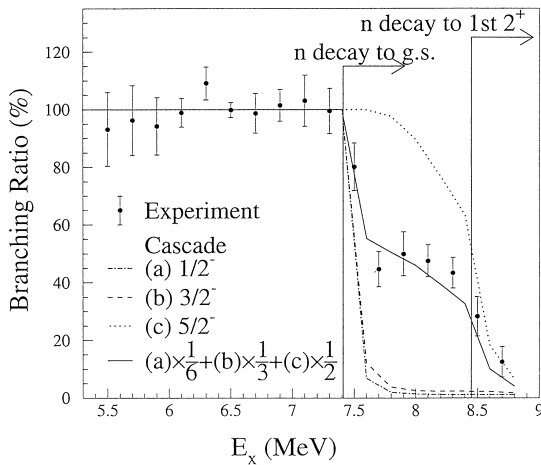


Fig. 4. Gamma-ray branching ratios Γ_γ/Γ_T for excited states populated by the $^{71}\text{Ga}(^3\text{He},t)^{71}\text{Ge}$ reaction as a function of excitation energy E_x in ^{71}Ge . S_n and $S_{n'}$ show the threshold energies for neutron decay to the 0^+ ground state and the 2^+ excited state in ^{70}Ge , respectively. CASCADE calculations for GT states with $J^\pi = 1/2^-, 3/2^-$ and $5/2^-$ are shown by appropriate lines with (a), (b) and (c), respectively. The solid line shows the summed values with the population weights of $(2J+1) = 2, 4$ and 6 .

Gamma branches to low-lying states in ^{71}Ge from IAS, which is far above the neutron threshold energy, are also not appreciable. In fact, IAS decays to ^{70}Ge by emitting neutrons as is naturally expected for the high-lying IAS with the considerable spreading width. This is consistent with the $(^3\text{He},t\gamma)$ experiment at $E(^3\text{He}) = 30$ MeV [15], where IAS is populated preferentially in contrast to the present case at $E(^3\text{He}) = 450$ MeV, where GT states are populated preferentially.

These observed features of Γ_γ/Γ_T are explained qualitatively as follows. Excited GT states in ^{71}Ge populated by the $^{71}\text{Ga}(^3\text{He},t)$ reaction are considered to have spins and parities of $J^\pi = 5/2^-, 3/2^-$ and $1/2^-$ with ratios of $(2J+1) = 6, 4$ and 2 , respectively. Unbound states with $J^\pi = 3/2^-$ and $1/2^-$ may decay by emitting p-wave neutrons to both the 0^+ ground state and 2^+ excited state in ^{70}Ge , while those with $J^\pi = 5/2^-$ decay by emitting f-wave neutrons to the 0^+ ground state and p-wave neutrons to the 2^+ excited state. The neutron emission from the GT states with $J^\pi = 5/2^-$ to the 0^+ ground state in ^{70}Ge is suppressed greatly because of the centrifugal barrier for the f-wave neutrons. The neutron decays from the GT states in ^{71}Ge to the 0^+ ground state in ^{70}Ge are, in general, reduced much because of the configuration mismatch between them. Consequently, the GT states with $J^\pi = \frac{5}{2}^-$ just above S_n decay to the states in ^{71}Ge mainly by emitting γ -rays, not to the 0^+ state in ^{70}Ge by emitting the f-wave neutrons.

A quantitative calculation was carried out by means of the CASCADE code to evaluate the γ branching ratio. The calculated ratios reproduce the observed one, as shown in Fig. 4.

The GT strengths for ground and excited states in ^{71}Ge were obtained from the observed $(^3\text{He},t)$ cross sections at the forward angle ($\theta_t \sim 0^\circ$), as shown in Table 1. Here, the GT strengths were normalized to the ground-state value derived from the beta-decay ft -value. In this way, a common systematic error for absolute cross-sections and for the corresponding $B(\text{GT})$ values could be avoided. There remains, however, the uncertainty due to energy and state dependence of converting the forward-angle cross-sections into $B(\text{GT})$ values for excited states. The excitation energy is at most 8 MeV, which is only 2% of the incident ^3He energy. Thus, the normalization factor

for the ground state is used for the excited states. The uncertainty for the B(GT) value due to this normalization procedures are at most 10%, i.e. $\Delta B(\text{GT}) \leq 0.3$. The other uncertainty for the high-lying unresolved states comes from the possible admixtures of the non-GT strengths with $\Delta J^\pi \neq 1^+$ at the forward angle. The admixture of the spin-dipole component with $\Delta l = 1$ are evaluated from the observed angular distribution over the angles of $\theta_i = 0^\circ$, 1° , and 2° . It is less than 7%, i.e. $\Delta B(\text{GT}) \leq 0.20$, in the present low-excitation region.

The solar- ν capture rates for the ground and excited states are evaluated for the SSM solar flux[9]. They are given in Table 2. Here the errors are mainly due to the errors for the solar flux. The error due to the systematic error of B(GT) for the excited states is as small as 2.0 SNU because of the small SNU value of 16 for the excited states other than the ground states.

Solar neutrinos are detected through the $^{71}\text{Ga}(\nu, e)^{71}\text{Ge}$ and $^{71}\text{Ga}(\nu, e\gamma)^{71}\text{Ge}$ processes by counting the number of produced ^{71}Ge nuclei. Solar-neutrino absorption rates for individual neutrino sources, together with the SSM predictions [9] are listed in Table 2. They have been obtained by folding the ν energy spectra for all the solar- ν

Table 1

The B(GT) values and solar neutrino capture rates obtained via the $^{71}\text{Ga}({}^3\text{He}, t)^{71}\text{Ge}$ reaction at 450 MeV

E_x (MeV)	B(GT) ^{a)}	Capture rate (SNU) ^{b)}
0.000	$(8.91 \pm 0.13) \times 10^{-2}$	114.9 ± 11.8
0.175	$(4.91 \pm 1.77) \times 10^{-3}$	1.75 ± 1.01
0.500	$(2.08 \pm 0.21) \times 10^{-2}$	3.35 ± 1.10
0.83	$(2.37 \pm 0.23) \times 10^{-2}$	$(7.51 \pm 3.37) \times 10^{-1}$
1.16	$(2.33 \pm 0.24) \times 10^{-2}$	$(8.11 \pm 1.89) \times 10^{-1}$
1.36	$(2.01 \pm 0.23) \times 10^{-2}$	$(2.78 \pm 1.31) \times 10^{-1}$
1.58–7.42	2.88 ± 0.09	9.52 ± 3.73
7.42–8.46	0.74 ± 0.10	0.34 ± 0.15
total	$3.81 \pm 0.15^{\text{a)}}$	$131.7 \pm 18.4^{\text{b)}}$

^{a)} The B(GT) values are normalized to the ground state value obtained from the β -decays ft value. Errors given are statistical ones. Systematic errors for excited states are 12%. The total systematic error is $\Delta B(\text{GT}) = 0.4$. ^{b)} The neutrino capture rates are evaluated for the solar- ν flux given by SSM (Ref. [9]). Errors include those of the ν -flux and the experimental statistical ones. The systematic error for the total rate is about 2.0 SNU. ^{a), b)} Data for the bound region, see also Ref. [10].

Table 2

Solar- ν absorption rates for individual sources

Source	SNU ^{a)} total	SNU ^{b)} neutron unbound	SNU ^{c)}
pp ⁸	70.8 ± 0.2	–	70.8
B	12.9 ± 0.4	0.34 ± 0.06	14.0
hep ¹³	$(5.62 \pm 0.16) \cdot 10^{-2}$	$(0.28 \pm 0.06) \cdot 10^{-2}$	0.06
N ¹⁵	3.74 ± 0.07	–	3.8
O ¹⁷	5.81 ± 0.14	–	6.1
F	$(6.01 \pm 0.15) \cdot 10^{-2}$	–	0.06
pep	2.94 ± 0.09	–	3.0
⁷ Be	35.0 ± 0.7	–	34.3
total	$131.7 \pm 1.6^{\text{d)}}$	0.34 ± 0.06	132^{+20}_{-17}

^{a)} Present experimental results. Errors given are statistical ones.

^{b)} As ^{a)} But from neutron-unbound region in ^{71}Ge . ^{c)} Estimation given in Ref. [9]. ^{d)} The total capture rate has the statistical and systematic errors of 1.6 and 2.0 due to the statistical and systematic errors of B(GT) and error of 16.4 for the solar- ν flux.

sources with the B(GT) distribution as obtained from the present measurement. The total absorption rate is thus $131.7 \pm 1.6(\text{exp}) \pm 2.0(\text{sys}) \pm 16.4(\text{sun})$, with (exp) and (sys) being the experimental statistical and systematic errors due to the present experiment and (sun) the error of the solar- ν flux in the SSM.

The contributions from the neutron-unbound region to the ^8B neutrinos are 0.3 SNU. This is about 2.5% of the total absorption rate for the ^8B neutrinos. The present data indicate quantitatively finite contributions to the solar-neutrino absorption through particle-unbound states.

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